# The Potential for Using LEO Telecommunications Constellations to Support Nanosatellite Formation Flying

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## SECTION I - MOTIVATION

During the past several years, an interest has grown in using commercial telecommunications techniques to supply Telemetry and Command (T&C) services. An initial study of this concept was performed for NASA in 1996[1]. Recently, the National Aeronautics and Space Administration (NASA) Space Operations Management Office (SOMO) has outlined plans to utilize satellite-based telecommunications services to support space operations [2] in space missions over the next several decades. NASA currently obtains the bulk of its telecommunications services for earth-orbiting satellites via the existing, government-owned and controlled Space Network (SN) system. This system consists of the constellation of Tracking and Data Relay Satellites (TDRS) in Geostationary Earth Orbit (GEO) and the associated ground terminals and communications infrastructure. This system is valuable and effective for scientific satellites costing over one million dollars. However, for smaller satellites, this system becomes problematic due to the cost of transponders and support infrastructure. For example, the current 3 Corner Satellite project has a cost cap of $100,000.00 for the total satellite price. The nominal transponders for using the TDRS cannot be obtained for a cost in dollars, and size, weight, or power that the 3 Corner Satellite project can afford. For these types of nanosatellite missions, alternatives that fit the mission cost and satellite profiles are needed. In particular, low-cost access using existing commercial infrastructure would be useful to mission planners. In particular, the ability to obtain low data rate T&C services would be especially valuable. The nanosatellites generally have low T&C requirements and therefore would benefit from using commercial services that could operate in the 2400 bps - 9600 bps range, especially if contact times longer than the 5 - 10 minute ground station passes could be found.

Taking the 3 Corner Satellite [3] program as a typical nanosatellite mission, the satellite constellation needs communications services to provide

    a.      Satellite crosslinks for data services such as GPS position, status, coordination between the nanosatellite constellation members

    b.      Forward/return links for health and welfare data checking and command uploads between the individual satellites and the ground control points

    c.      Access to satellites at times other than when the nanosatellite is visible from a fixed ground station (about every 10 hours)

    d.      Data transport for up to 8 Mbyte per day from each of three satellites in the

constellation.

In designing the satellite constellation mission plan, we are led to inquire if the mission can utilize the existing commercial LEO telecommunications satellites to provide these services and contacts? These commercial telecommunications structures offer several advantages for the nanosatellite design, including

a.   The ability to have simultaneous, bidirectional contact between the ground stations and each of the nanosatellite constellation members.  This is almost impossible to achieve with existing ground station technology at small cost since the satellites will be given only one forward and return frequency pair and all three satellites will usually be visible simultaneously from a single ground station.  The constellation members need to time share these frequencies with existing ground stations.  The ability to use LEO telecommunications satellites would make mission coordination much easier than ground station technology currently allows within the nanosatellite budget constraints.

b.   The use short-message service or paging service for crosslinks to provide the GPS positioning information and short coordination messages.

c.   Global coverage to provide the potential for many more contacts than traditional ground stations and allowing T&C services.

d.   Leveraging commercial communications protocols such as the Point-to-Point Protocol to allow easy use of data communications and quick interconnection with ground stations.

e.   Light-weight and relatively-low-cost communications hardware.  Current cellular telephone technology often integrates easily with computers so it is expected that the satellite cellular telephone would integrate with the on-board computer systems in a similar manner.  An example of how this might be done is illustrated in Figure 1. The PC-104 format illustrated there is being considered for the 3 Corner Satellite constellation on-board computer system.  As part of this design, we are looking into PC-104 computer systems that have TCP/IP support as part of the resident operating system.  A CPU board in this hardware format is produced by Arcom and other vendors.  The Arcom realization is illustrated in Figure 2.  Support chips such as the TCP/IP in silicon realization produced by Seiko is illustrated in Figure 3.  Both of these options would provide realistic interfaces to cell phone service providers, e.g. a serial PPP interface.

From this, it is expected that further investigation of this concept is warranted.  In the next section of this report, we will examine current candidate systems for using cellular telephones from space. Then we will examine current usage issues that are potential stopping points for the technology being used in the near future.
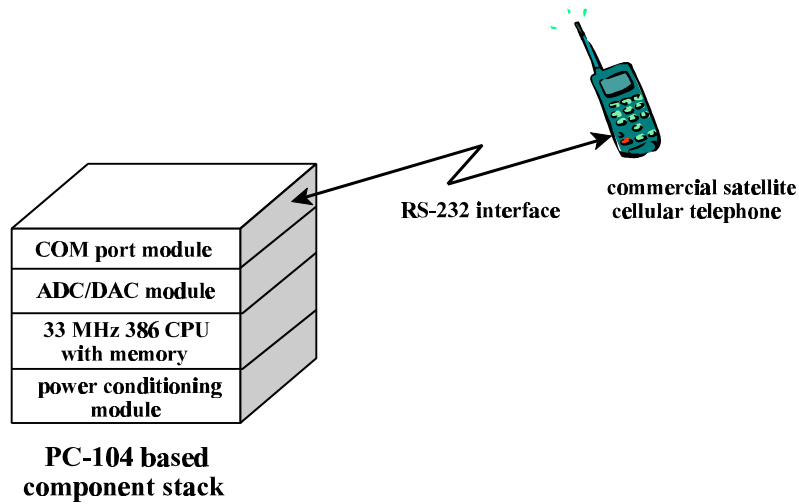
**Figure 1** - Connection between a candidate nanosatellite on-board computer system and satellite cellular telephone system for use inside a nanosatellite.



**Figure 3** - Seiko TCP/IP support chip.

**Figure 2** - Arcom PC-104 CPU with resident TCP/IP support in the operating system.

## SECTION II - CANDIDATE SYSTEMS

The first big question that needs to be resolved is which LEO telecommunications satellite systems can we consider for this task. A quick review of the current state of the business is really not encouraging. For example, ICO and Iridium have undergone bankruptcy problems and as of this

date, the Iridium constellation is scheduled for de-orbiting later this year. Currently, there are two operating companies supplying LEO satellite constellation services to ground-based users: Orbcomm and Globalstar. Both of these constellations have undergone some financial strains over the past year but they are providing commercial services. The Teledesic constellation is still under development for future deployment.

For the purposes of this study, we will look at the Globalstar and Orbcomm constellations. Globalstar provides S-Band services to users while Orbcomm provides UHF/VHF services to users. The Globalstar constellation is composed of 48 satellites in a 1410-km circular orbit arranged as eight orbital planes with inclinations of 52°. The system ground traces are illustrated in Figure 4. The Orbcomm constellation is composed of approximately 48 satellites at an 825-km circular orbit. Sixteen of the satellites are in a near-polar orbit (70° or 108°) while the remainder are in a 45° inclination orbit. The system ground traces are illustrated in Figure 5.

For the purposes of this study, we will model the user satellites by the 3 Corner Satellite constellation of three satellites flying in close formation with an orbital altitude of 350 km and an orbital inclination of either 28.5° or 52°. At the moment, the 3 Corner Satellite constellation's orbit is not yet set but we believe it to be bounded by those parameters.

In this study we will examine both of these systems for the following parameters:

1.     The frequency and duration of contact between a given LEO user satellite and the service provider constellation
2.     The expected Doppler shift to the service frequency due to the relative motion of the satellites

These are the primary orbital parameters that can be determined at the moment using the Satellite Tool Kit (STK) [4] software for simulation purposes. Orbital elements for the Globalstar and Orbcomm constellation members were obtained from [5].


## SECTION III - USAGE ISSUES

To use the cell phones from satellites, we must consider the following topics for the system:

1.     Access time as a function of orbital parameters in the target satellite and the LEO constellation
2.     Doppler shifts to the transmission frequencies caused by the relative motions of the satellites
3.     Power control and antenna beam issues so that the user satellite does not harm the service provider satellite system.
4.     Regulatory restrictions on services, frequencies, and modes of operation, and
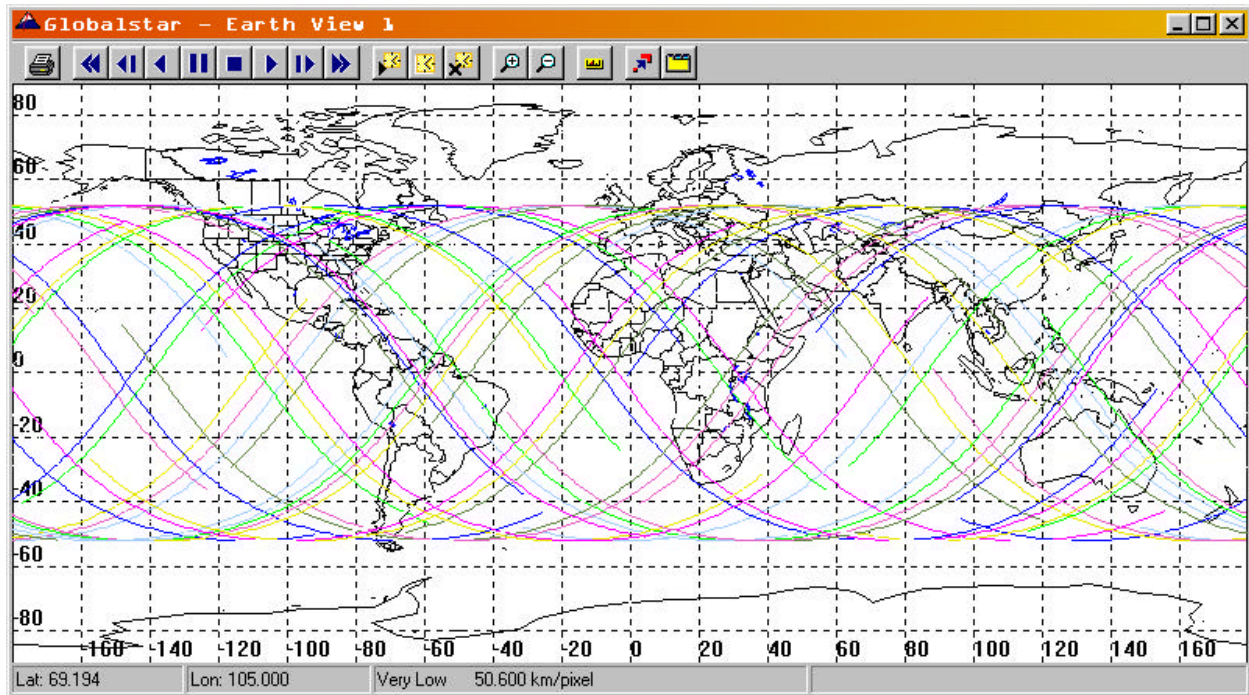5.     Billing and access validation techniques.

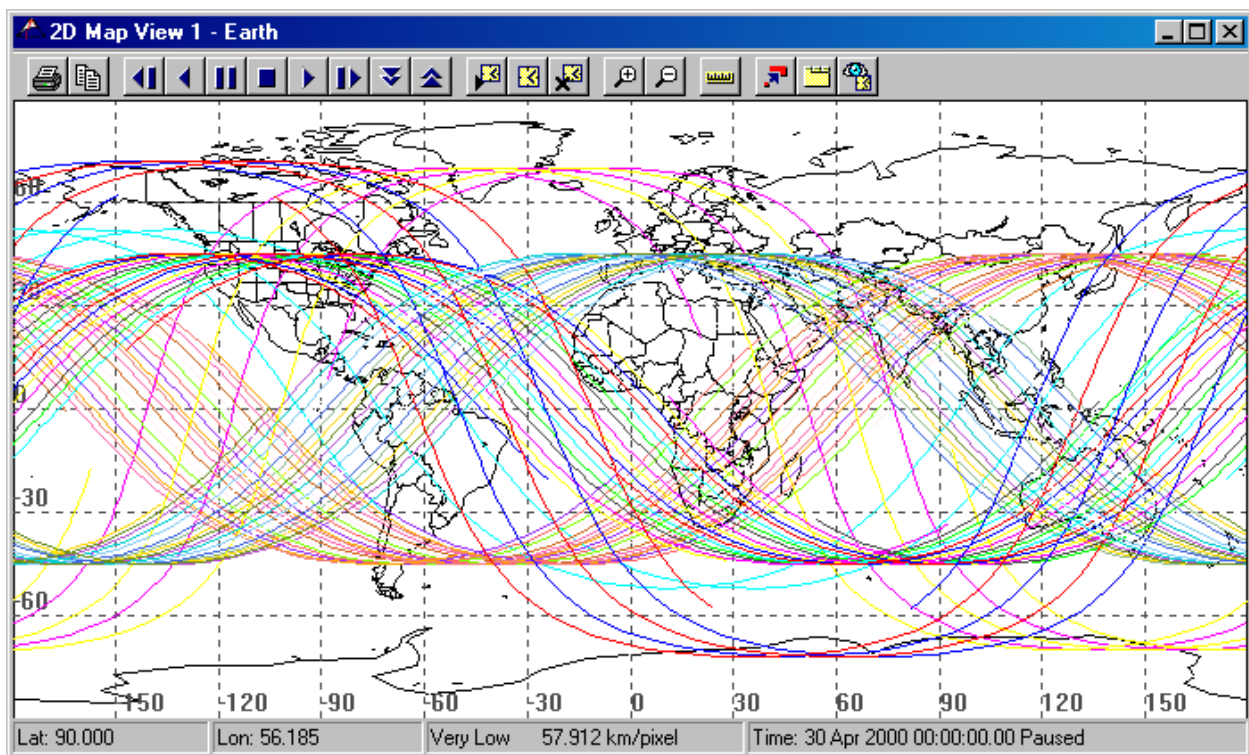**Figure 4** - Globalstar ground tracks to illustrate the constellation orbit.



**Figure 5** - Orbcomm ground tracks to illustrate the constellation orbit.

In this section, we will look at the orbital access times and the Doppler shifts associated with the access between a LEO user satellite and the LEO service provider constellation. The access is simulated with the STK software using a target satellite at 350 km orbit with an inclination angle set to either 28.5° or 52°.

## III.1   ORBITAL ACCESS

The orbital access opportunities for the Globalstar constellation are simulated over a 24-hour period with the results given in Figures 6 and 7. Figure 6 corresponds to a user satellite in a 350-km, 28.5° inclination orbit while Figure 7 corresponds to a 52° inclination orbit. In these figures, the position across the x-axis corresponds to a different satellite within the system. As one goes up the figure at constant x position, one is seeing access opportunities at different times through the day. The height of the trace is an indication of the length of the contact. The average contact opportunities are given for both user satellite orbital inclinations in Table 1 and histograms of the access times for both inclinations are given in Figures 8 and 9. From Figures 6 through 9, we can see that there are significantly-long passes for the user to access the Globalstar constellation. We can also see that the 52° orbital inclination performs much better because that closely matches the orbital inclination of the Globalstar constellation. In effect, the user is flying in formation with the service provider and the long, greater than 30 minute, access times occurs. With these access times, we can expect a data throughput like that found in Table 2. With these throughput levels, the 3 Corner Satellite constellation could easily achieve its required daily data transport needs using this technology. The data throughput listed in Table 2 is per satellite per call of the given duration. Depending upon the orbit of the user satellites, there can be several such calls per day and all of the satellites in the nanosatellite constellation have the potential to have one of these calls ongoing simultaneously. This would not be possible with single frequency access of a terrestrial ground station.

| Table 1.  Globalstar Access Opportunities | | |
| --- | --- | --- |
| **User Orbital Inclination** | **Average Access Time** | **Maximum Access Time** |
| 28.5° | 8.4 minutes | 19.3 minutes |
| 52° | 8.8 minutes | 38.7 minutes |

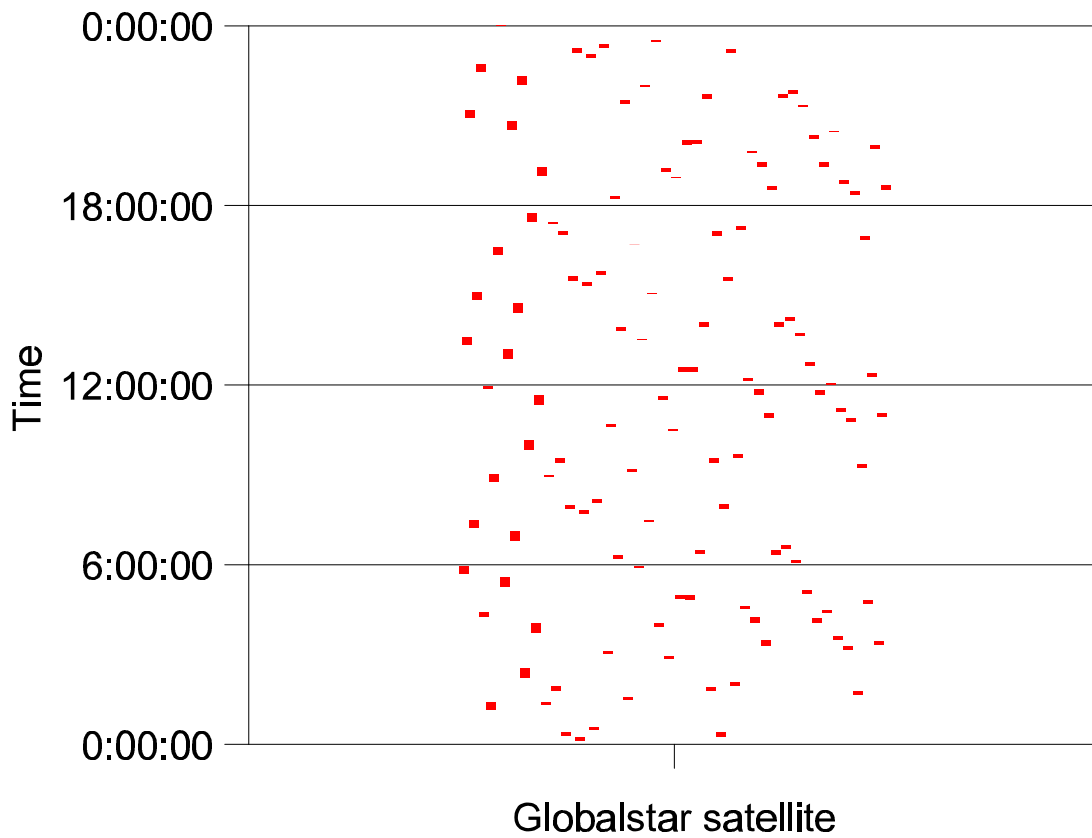| Table 2. Data Throughput as a Function of Access Time and Data Rate | | |
| --- | --- | --- |
| **Data Rate** | **8-minute pass** | **30-minute pass** |
| 2400 bps | 144,000 bytes | 540,000 bytes |
| 4800 bps | 288,000 bytes | 1,080,000 bytes |
| 9600 bps | 576,000 bytes | 2,160,000 bytes |

**Figure 6** - Orbital access opportunities from a LEO user to the Globalstar constellation when the user is in a 350-km, 28.5° inclination orbit. Position across the x-axis corresponds to satellite number in the Globalstar system.

Similar to the Globalstar case, the orbital access opportunities for the Orbcomm constellation are simulated over a 24-hour period with the results given in Figures 10 and 11. Figure 10 corresponds to a user satellite in a 350-km, 28.5° inclination orbit while Figure 11 corresponds to a 52° inclination orbit. As before, the position across the x-axis corresponds to a different satellite within the system. As one goes up the figure at constant x position, one is seeing access opportunities at different times through the day. The height of the trace is an indication of the length of the contact. The average contact opportunities are given for both user satellite orbital inclinations in Table 3 and histograms of the access times for both inclinations are given in Figures 12 and 13.

From the graphs, we see that the Orbcomm constellation does not have as favorable access to the 3 Corner Satellite user as did Globalstar but the access times would still permit significant data throughput to support T&C services. From the access histograms, we see a bi-modal distribution
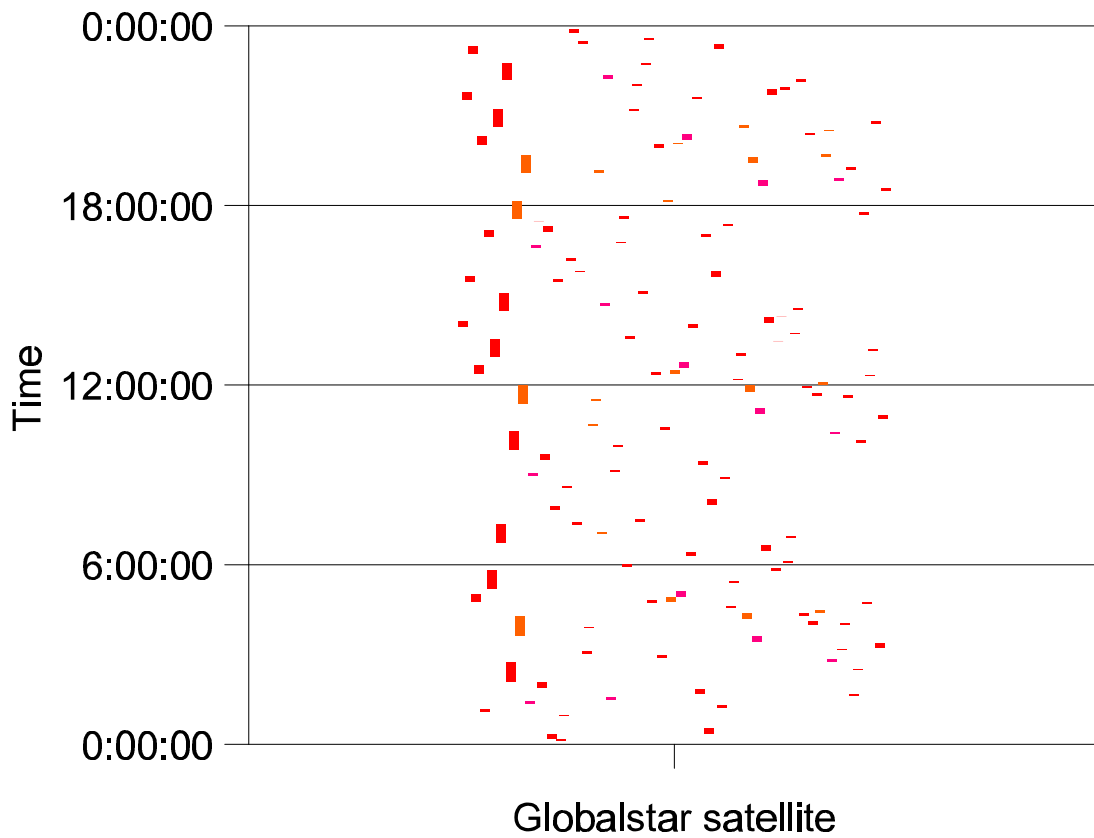
**Figure 7** - Orbital access opportunities from a LEO user to the Globalstar constellation when the user is in a 350-km, 52° inclination orbit.  Position across the x-axis corresponds to satellite number in the Globalstar system

caused by the two orbit planes of the Orbcomm constellation.  In Table 3, we see that the average pass duration is shorter as is the maximum pass duration.  With the Orbcomm constellation, the 3 Corner Satellite test orbits at 28.5° and 52° orbital inclination do not fly in formation with the Orbcomm satellites so we do not get the long passes as with Globalstar.

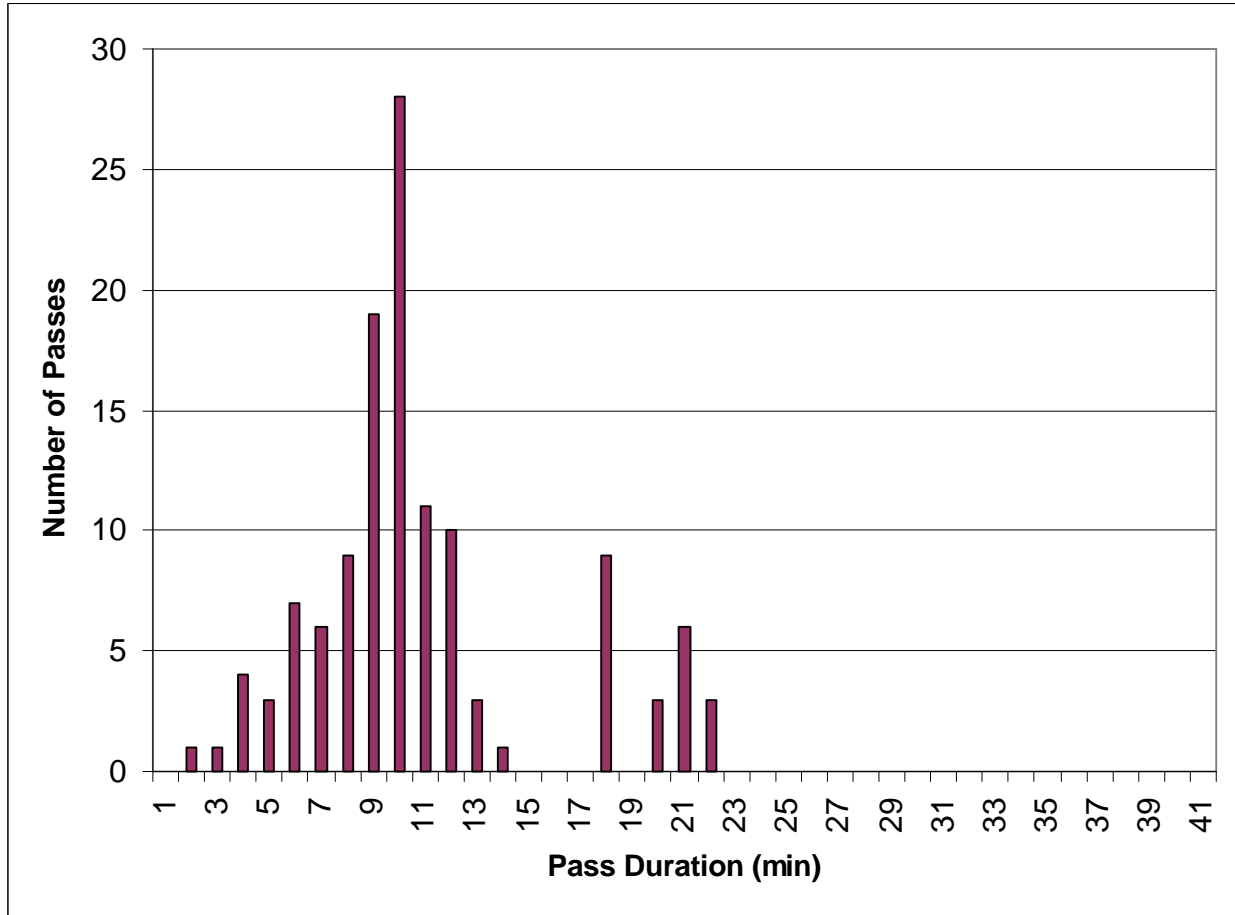| Table 3.  Orbcomm Access Opportunities | | |
|---|---|---|
| **User Orbital Inclination** | **Average Access Time** | **Maximum Access Time** |
| 28.5° | 6.1 minutes | 11.3 minutes |
| 52° | 5.2 minutes | 10.2 minutes |

**Figure 8** - Histogram of access times for a user satellite in a 350-km, 28.5° inclination orbit to the Globalstar constellation.

Related to the access times is the throughput with real systems. Figure 13 illustrates the expected transfer times for a 1kByte and 1Mbyte file over a channel with 0, $10^{-6}$, and $10^{-5}$ bit error rates. Until the bit error rates approach the low value of $10^{-5}$, the throughput of these typical files can be accomplished in the range of access times simulated here. Naturally, the short access times will require short files or shorter file segments. However, several 1-kB files or a significant portion of a 1-MB file can easily be accomplished with even the shorter access times.
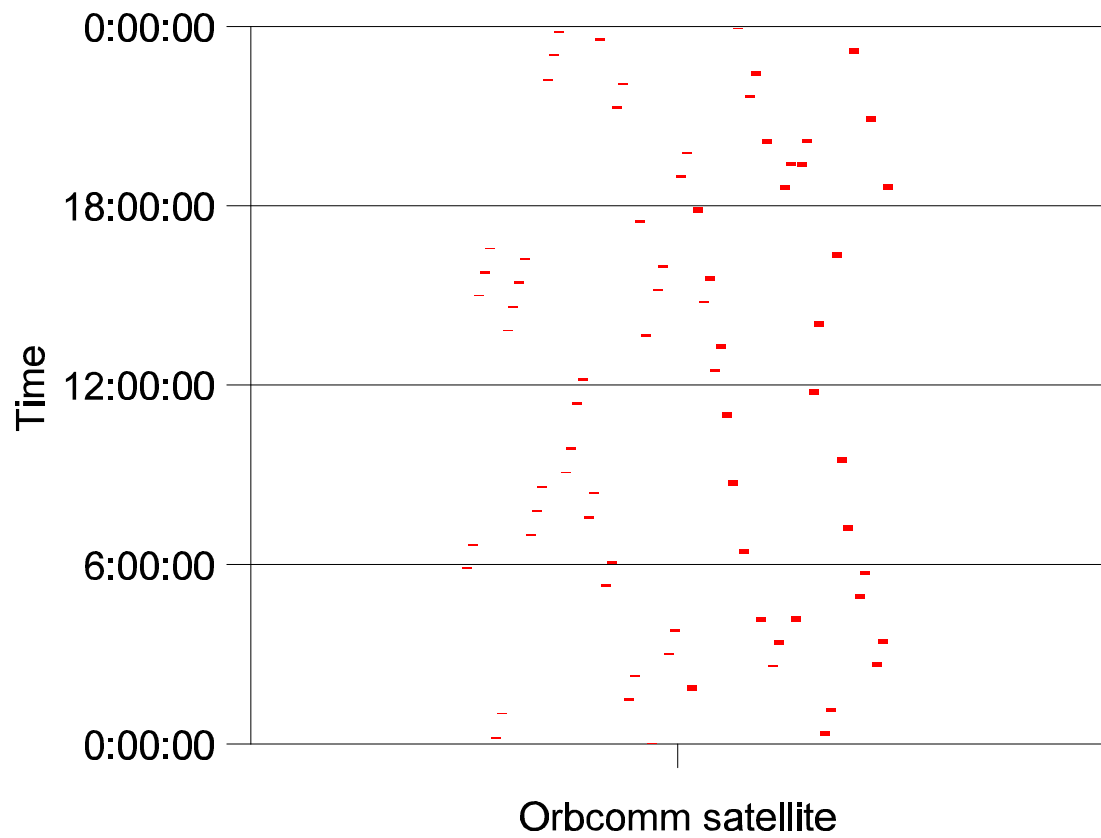
**Figure 9** - Orbital access opportunities from a LEO user to the Orbcomm constellation when the user is in a 350-km, 28.5° inclination orbit. Position across the x-axis corresponds to satellite number in the Orbcomm system.
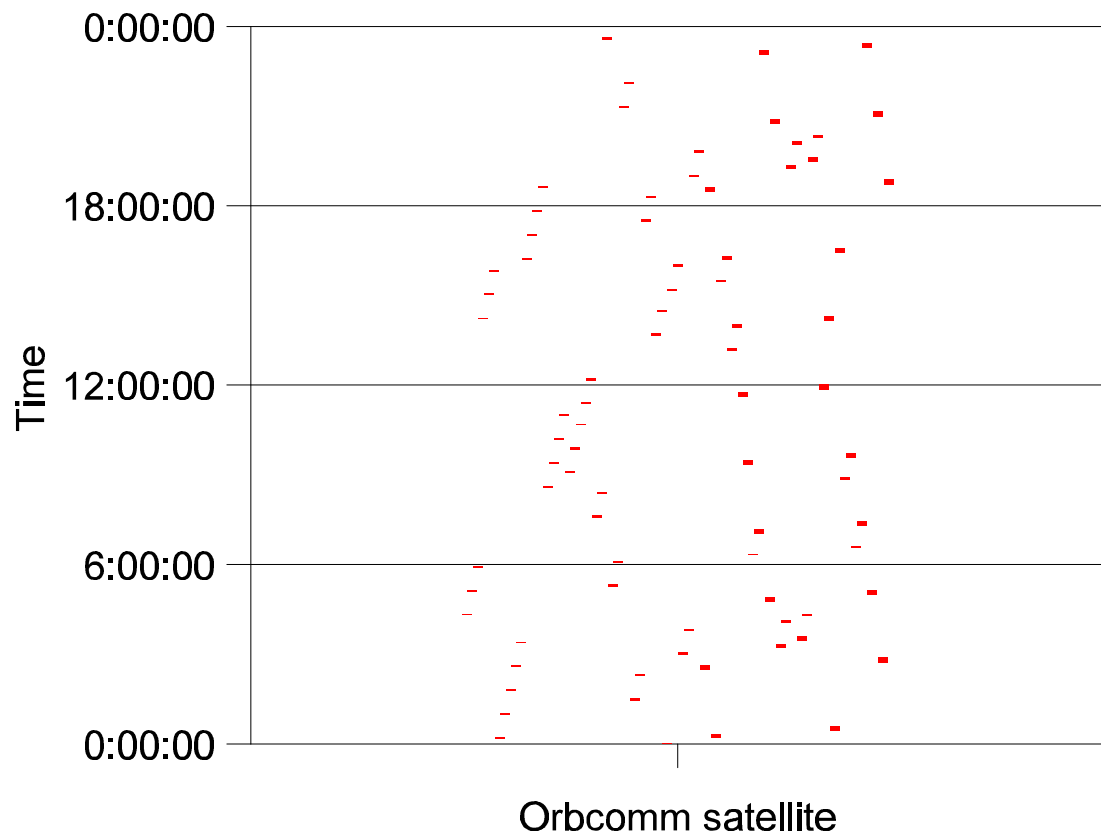
**Figure 10** - Orbital access opportunities from a LEO user to the Orbcomm constellation when the user is in a 350-km, 52° inclination orbit. Position across the x-axis corresponds to satellite number in the Orbcomm system.
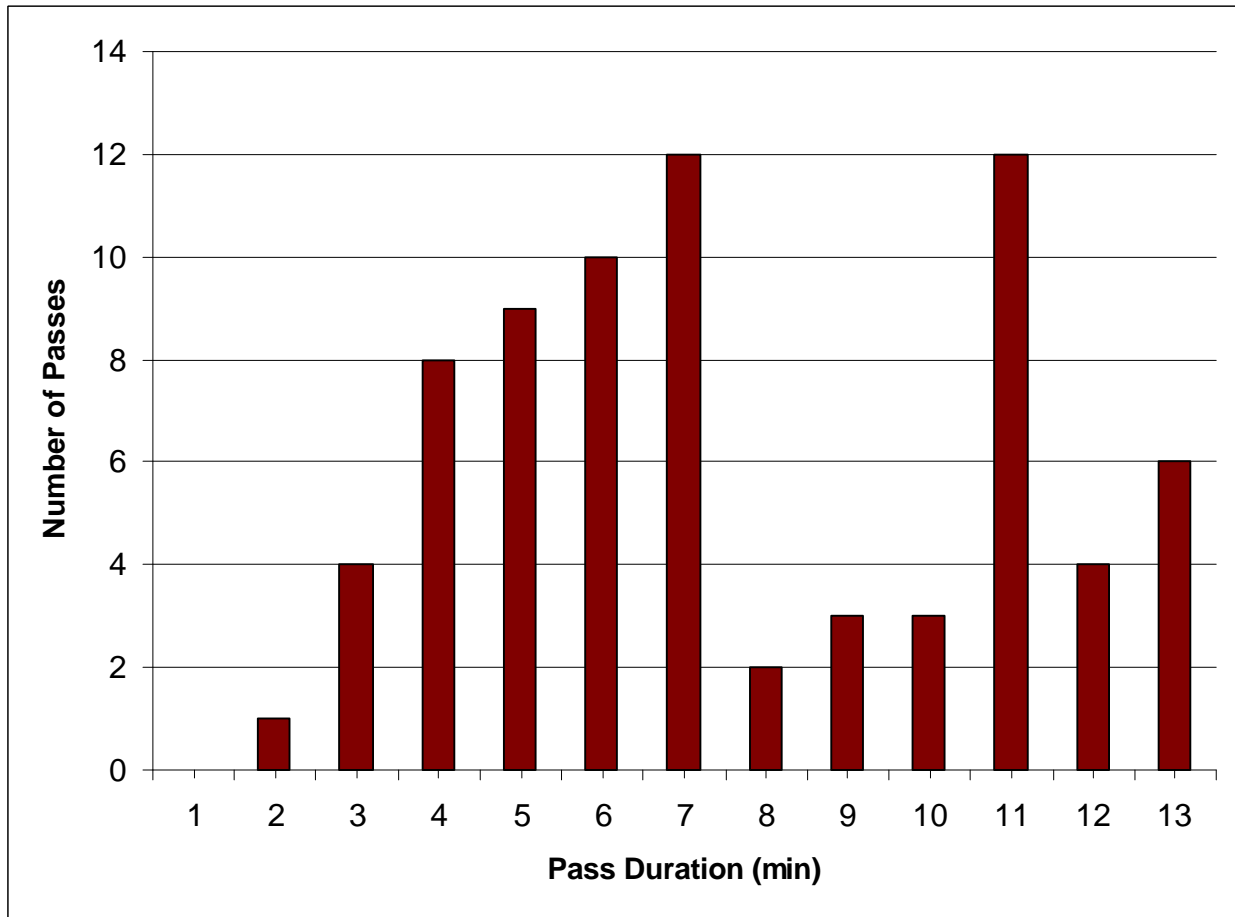
**Figure 11** - Histogram of access times for a user satellite in a 350-km, 28.5° inclination orbit to the Orbcomm constellation.
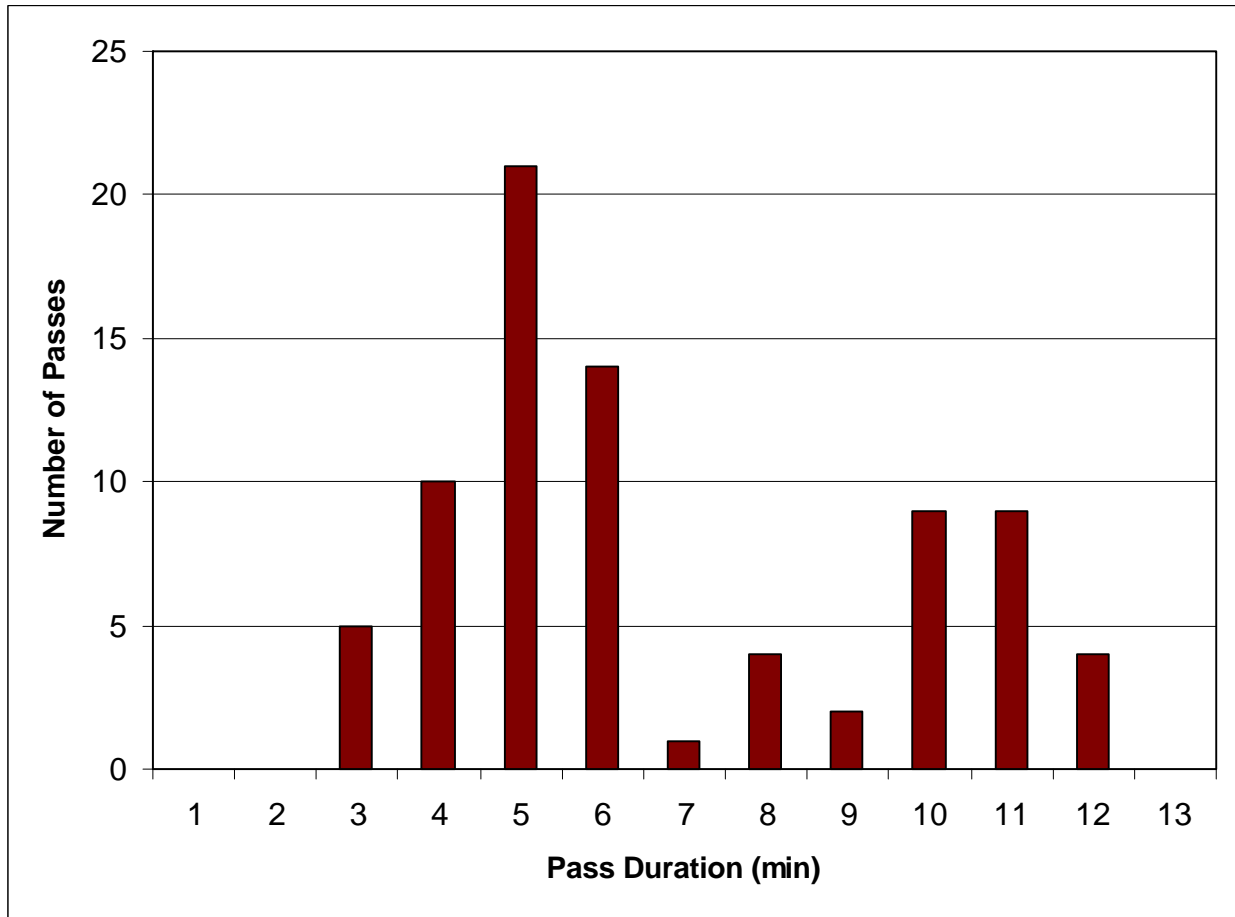
**Figure 12** - Histogram of access times for a user in a 350-km, 52° inclination orbit to the Orbcomm constellation.
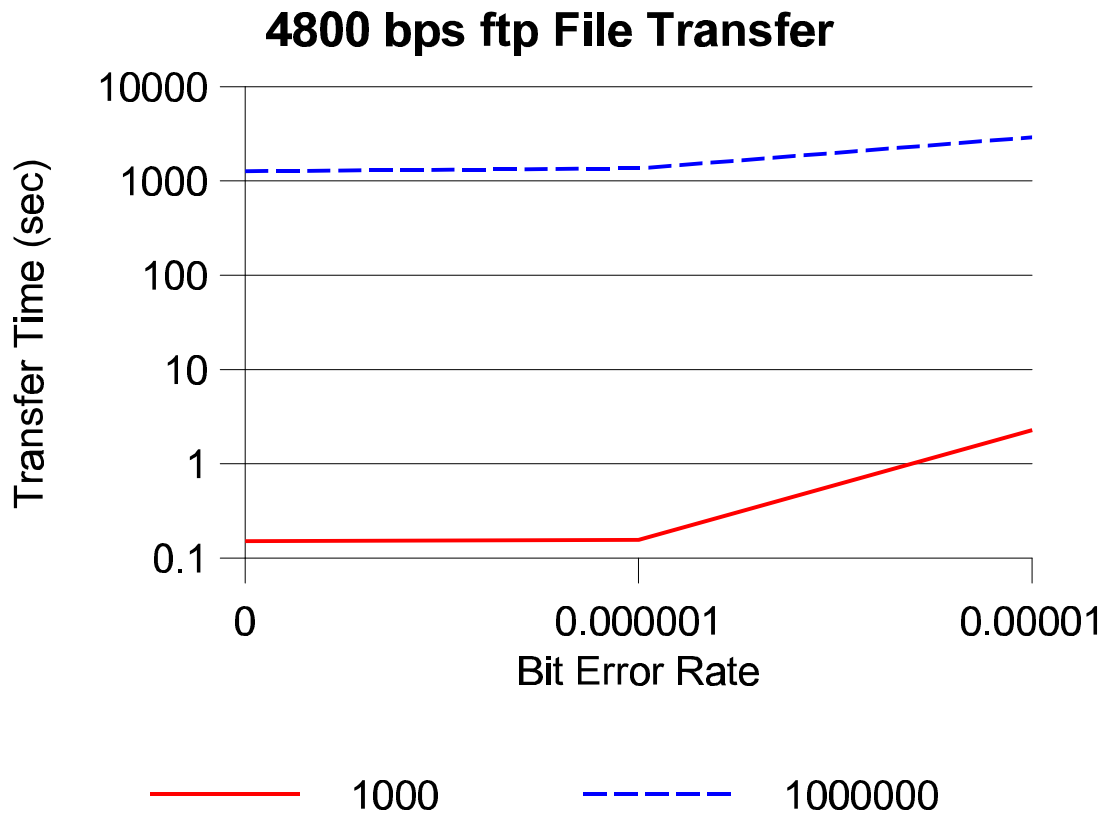
**Figure 13** - Transfer times for an `ftp` service as a function of a channel error rate for a nominal 4800 bps channel data rate.


### III.2   DOPPLER OFFSET

The motions of the satellites will cause a relative Doppler shift between the transmit and receive frequencies for the satellites.  The amount of the Doppler shift will be a function of the relative radial speeds of the satellites and the transmission frequency.  While the satellites are moving very rapidly with respect to the surface of the earth, they may not be moving rapidly with respect to each other along the radial vector separating the satellites.  From the STK simulations, we can examine the range difference between the satellites and use this to find the range rate or velocity along the radial direction separating the satellites.  Once that is determined, the Doppler shift as a function of frequency can be found.   The procedure is as follows:

Since STK simulates with a time step of one minute, the output report listing ranges and access times is in one-minute boundaries.  The range rate, $\dot{R}$, at a time $T_i$ is computed in terms of the range at

time at two adjacent simulation times using a first-order derivative estimator [6]

$$\dot{R}(m/\sec) = \frac{1000 * (R_{i+1} - R_{i-1})}{2 * 86400 * (T_{i+1} - T_{i-1})}$$

where $R_j$ is the range in km at time $T_j$ with $T_j$ being measured in days.  The ratio of the change in received radio frequency, $\Delta f$, to the transmission frequency, $f$, is then given by [7]

$$\frac{\Delta f}{f} \approx \frac{v}{c}$$

so this can be used to used to compute the frequency offset, $\Delta f$, given the transmission frequency, $f$.

Figure 14 shows the simulated Doppler shift between a member of the 3 Corner Satellite constellation and a member of the Globalstar constellation during one of the long access passes. During the pass, we see the 20-30 KHz Doppler spread in the received S-Band frequency with a null at mid pass.  Does this frequency shift compare with that found by a ground station?  A simulated Global star ground station pass is illustrated in Figure 15 to show that this is actually smaller than the constellation experiences in accessing a ground station.

As a comparison, the Doppler shift between the 3 Corner Satellite constellation and the Orbcomm constellation satellites is shown in Figure 16.  Since Orbcomm uses both VHF and UHF frequencies, both are given in Figure 16.  The magnitude of the shift is similar to that found between LEO satellites and fixed ground stations at these frequencies as well.
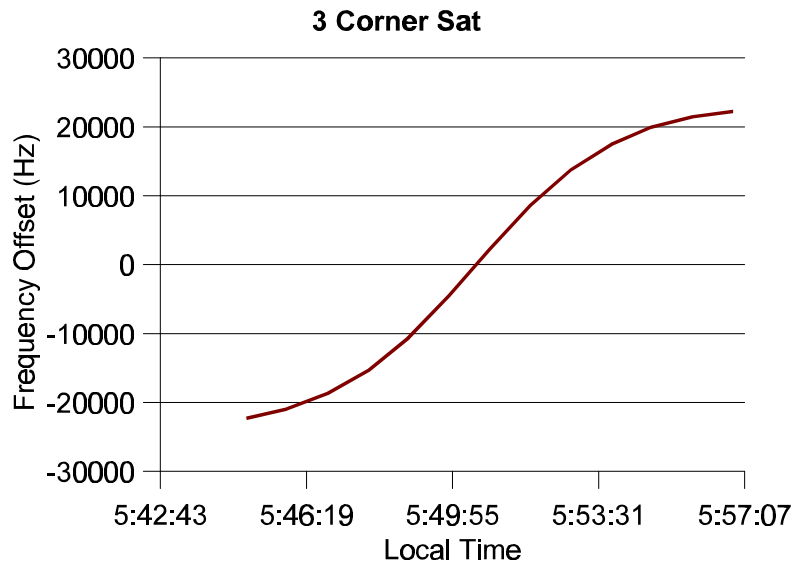
**3 Corner Sat**

**Figure 14** - Doppler shift between the 3 Corner Satellite constellation and the Globalstar constellation during a simulated satellite pass using S-Band access frequencies.
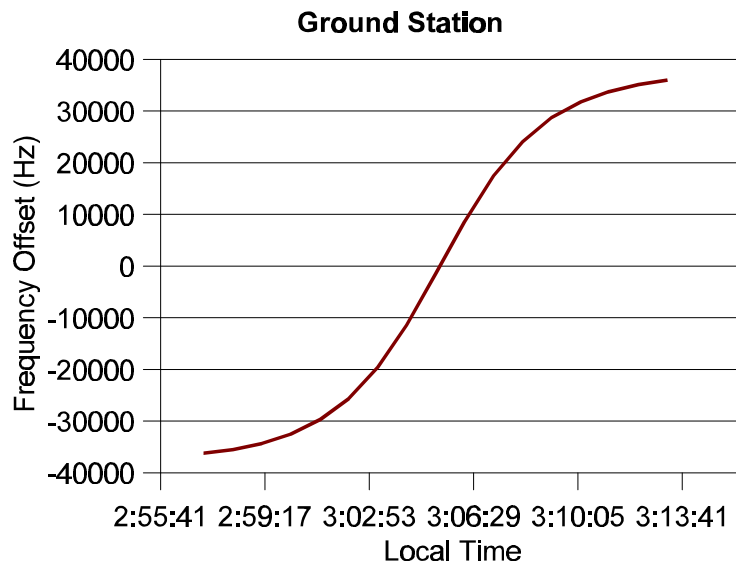


**Ground Station**

**Figure 15** - Doppler shift between a ground station located at 32° N latitude and the Globalstar constellation during a simulated satellite pass using S-Band access frequencies.
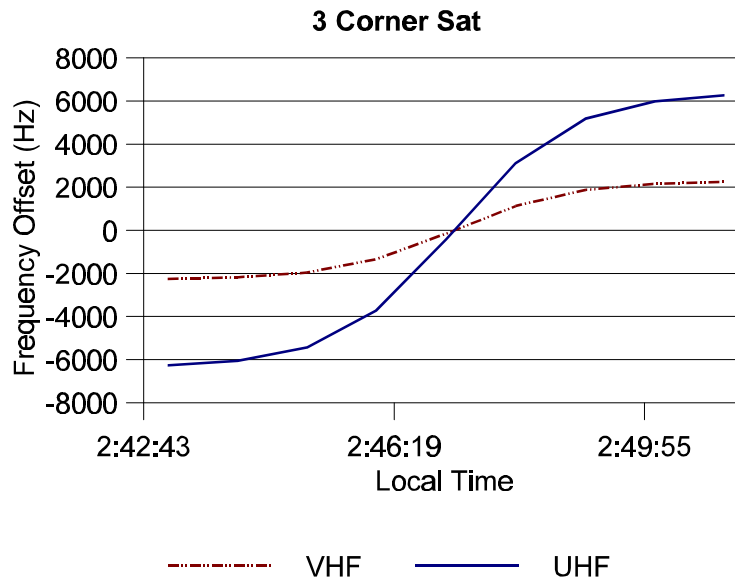
**Figure 16** - Doppler shift between the 3 Corner Satellite constellation and the Orbcomm constellation during a simulated satellite pass using VHF and UHF access frequencies.

## III.3   POWER AND ANTENNA BEACON ISSUES

The commercial LEO constellations are designed for longer link length than a LEO target satellite in orbit.  As the user satellite's orbit approaches the target satellite, it may need power control to avoid damaging the target satellite.  The user satellite designers will need to work closely with the service provider to avoid this problem and keep the power within acceptable levels.  This is not much different from the situation in terrestrial cellular networks.  The power control methods used in terrestrial systems will also be need to be found in LEO systems as well.

A related issue that has arisen with the Iridium constellation design is that the LEO constellation may have narrow spot beacons or other antenna issues that limit visibility of satellite from orbit.  These spot beacons limit the time that the user satellite can have a call active without some form of handover within the system.  The LEO telecommunications satellite system is designed for a ground-based user moving within the spot beacon of the satellite's field of view.  Based on the orbital parameters of the LEO telecommunications system, the system designers determine the maximum rate at which a ground-based user will transit the spot beacons.  The service provider company may have concerns that orbiting users will violate these access and handover restrictions and not be able to hold a proper service with the orbiting user.  This issue needs to be worked with the actual system designers.

## III.4  REGULATORY ISSUES

The Table of Frequency Allocations in the Manual of Regulations [8] does not show an allocation in the bands used by the LEO telecommunications satellites for space-to-space inter-satellite communications services. The links are regulated as space-to-ground or ground-to-space. The potential user of the LEO satellite constellation will need to work with the telecommunications provider and the appropriate regulatory agencies to either obtain an experimental license or some other means to have a "legal" access between the satellites.

## III.5  SYSTEM ACCESS ISSUES

A major concern pointed out by Globalstar [9] is that the billing and system access methodology used in the LEO telecommunications providers may prevent access by orbiting satellites. User validation and billing is based upon geographic location for entry into the system. The orbiting user satellite will not be tied to a specific gateway and therefore may not be viewed as a valid user in the system. To change the billing and access database for the communications provider may not be possible considering the relatively small number of orbital users versus the ground based users.

## SECTION IV - WHERE DO WE GO NEXT?

The largest impediment to further progress is the apparent lack of interest among service providers to work with us on this issue. Globalstar has indicated a reluctance to become involved and it appears that it would require a significant non-recurring engineering cost to make this happen – one that the service providers are not really interested in at the moment considering their place in the market and the current potential revenue market from the satellite community.

Further work issues of Doppler, power control, antenna access, handover, billing, etc., etc. with the service provider need to be addressed. However, considering their reluctance, this does not appear to be happening in the near future.

## SECTION V - CONCLUSION

It is our belief that using LEO telecommunications satellites from other LEO user satellites will come some day in the future. It seems to be a solution to the communications problems for the nanosatellite developers. It would provide improved access times. Most importantly, it would permit services to satellites flying too closely in formation to allow conventional ground station access with the limited forward and return frequency pairs. The use of LEO telecommunications satellites would also allow for inter-satellite links to send messages and data for mission planning and coordination purposes. The really major issues now seem to be regulatory and access control.

The radio frequency coordination bodies have not planned for this type of use with commercial systems nor have the service providers asked for this type of allocation. Until this issue is resolved – which may take many years – there may not be a "legal" way to use this service on a world-wide basis. The service provider companies need to be assured that there will be sufficient revenue from this type of operation to cover their changes in the software for user access and billing to permit this type of operation. The service provider companies will also need to work with the satellite developers to ensure signal compatibility with their systems. This is, again, a cost issue and not so much a major technical issue.

This is an interesting concept but not one where the technology and the needs matches the state of the regulations or the service providers.

## SECTION VI - ACKNOWLEDGMENTS

## SECTION VII - REFERENCES

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